National Institute for Occupational Safety and Health

NIOSH

Comments to MSHA

Comments of the National Institute for Occupational Safety and Health on the Mine Safety and Health Administration Request for Information on Exposure of Underground Miners to Diesel Exhaust

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The National Institute for Occupational Safety and Health (NIOSH) has reviewed the Mine Safety and Health Administration (MSHA) request for information (RFI) on *Exposure of Underground Miners to Diesel Exhaust* published in the *Federal Register* [81 FR 36826] on June 8, 2016. NIOSH supports the effort of MSHA to review its existing standards and policy guidance on controlling miners' exposure to diesel exhaust and offers the following responses (MSHA questions are in italics.)

Question A.1: ***Is there evidence that non-permissible, light-duty, diesel-powered equipment currently being operated in underground mines emits 2.5 g/hr of DPM or less? If so, please provide this evidence?***

Reply A.1: Yes, there is evidence that some equipment being operated in underground mines emits 2.5 grams/hour (g/hr) of diesel particulate matter (DPM) or less, but the evidence is mixed and not formally published. Analysis of the national coal inventory data [MSHA 2016a], collected under 30 CFR 72.520, shows that non-permissible, light-duty, diesel-powered equipment in U.S. coal mines is powered by a wide variety of MSHA-approved diesel engines. The engines fall into the following categories and percentages: 11-25 horsepower (hp) (3.2%), 25-50 hp (12.3%), 50-75 hp (21.8%), 75-175 hp (44.1%), and 175-750 hp (18.6%).

Furthermore, our analysis [Bugarski and Barone 2016] indicates that the engines in 788 out of 3,411 non-permissible, light-duty, diesel-powered equipment (approximately 23%) should emit less than 2.5 g/hr of DPM. Of the light-duty vehicles, 116 should meet the 2.5 g/hr criteria and are powered by diesel packages supplied by original equipment manufacturers (OEMs). These packages meet the 2.5 g/hr DPM criteria without any modifications, with the majority having outputs between 11 and 25 hp. The engines of the other 672 light-duty equipment were retrofitted by a third party with diesel particulate filters (DPFs) or filtration systems with disposable filter elements (DFEs) to meet the 2.5 g/hr DPM criteria. Because laboratory or in-use particulate matter (PM) emissions data are not available for the majority of the engines, no firm evidence exists that these vehicles, when operated in underground coal mines, emit less than 2.5 g/hr of DPM.

Finally, the national coal diesel inventory data indicate that at least 97% of permissible and 90% of non-permissible heavy-duty (hd) equipment emit less than 2.5 g/hr of DPM, and that at least 50% of non-permissible light-duty (ld) equipment (including generators and compressors) emit more than 5 g/hr of DPM [MSHA 2016a].

Question A.2: ***What administrative, engineering, and technological challenges would the coal mining industry face in meeting a 2.5 g/hr DPM emissions level for non-permissible, light-duty, diesel-powered equipment?***

Reply A.2: Our analysis of the engines currently used by the U.S. coal mining industry [MSHA 2016a] indicates the following administrative, engineering, and technological challenges:

- *Engines rated below 25 hp.* Approximately 88% of sub-25 hp engines currently used in underground coal mines meet the 2.5 g/hr DPM criteria. The vehicles powered by Kubota D902-E3-UV (07-ENA090004), Kubota D1105-E3-UV (07-ENA110010), Kubota D1105-E4-UV (07-ENA110011), Mitsubishi S3L2-Y361DPH (07-ENA110016), and Daihatsu DM950DTH

(07-ENA070004) contribute less than 2.5 g/hr of DPM [MSHA 2016a]. Some of these engines also meet U.S. Environmental Protection Agency (EPA) Tier 4 final standards (PM < 0.40 g/brake horsepower-hour (bhp-hr) [EPA 2016].

- *Engines rated between 25 and 75 hp.* Approximately 9% of engines with outputs between 25 and 75 hp meet the 2.5 g/hr DPM criteria [MSHA 2016a]. In the majority of the cases, these low DPM emissions were achieved primarily by the retrofit-type DPFs and, in a few cases, by filtration systems with DFE. Exhaust aftertreatment might be an option for vehicles that have enough space for installation of such a system. Replacement of existing engines with same-size engines that meet EPA Tier 4 final standards [EPA 2016] is one of the alternative solutions. All EPA Tier 4 final engines (PM< 0.022 g/bhp-hr) with outputs between 25 and 75 hp should meet 2.5 g/hr standard.

- *Engines rated between 75 and 175 hp.* Data available in the national coal diesel inventory [MSHA 2016a] indicate that DPM emissions from approximately 36% of engines rated between 75 and 175 hp are maintained under 2.5 g/hr by retrofit-type DPFs or filtration systems with DFEs. In general, the technology is available to reduce emissions from the currently used engines in this size range. However, due to a wide variety of engine/vehicle designs and duty cycles, the available solutions need to be evaluated for each individual case. Controlling DPM emissions from approximately 0.7% of engines in this category that emit more than 20 g/hr of DPM (e.g., Caterpillar 3304 PCNA, Caterpillar 3306 PCNA) is technologically or economically challenging [Bugarski and Barone 2016]. The efficiencies of two MSHA-verified high-temperature DFEs are listed as 83% and 80% (at 650 °F) [MSHA 2016b]. Reducing DPM emissions from 20+ g/hr to 2.5 g/hr with 83% or less efficient filter is mathematically impossible. High DPM emissions translate to short life expectancy of the filters. The DFEs are often changed in intervals not longer than 8 hours which is relatively costly. Replacing existing engines with same-size engines that meet EPA Tier 4 final standards (PM < 0.015 g/bhp-hr) [EPA 2016], and therefore should not emit more than 2.5 g/hr, is one of the alternative solutions. In order to ensure simultaneous reduction in PM mass and number emissions, it is necessary to use solutions that involve exhaust filtration and minimize the adverse effects of exhaust aftertreatment systems on particulate number emissions [Thiruvengadam et al. 2012; Herner et al. 2011; Robinson et al. 2016].

- *Engines rated between 175 and 750 hp.* Approximately 6% of engines that are rated between 175 and 750 hp emit less than 2.5 g/hr [MSHA 2016a]. This level of DPM emissions has been achieved primarily by deploying the retrofit-type DPFs or, in few cases, filtration systems with DFE. Therefore, it appears that the technology is available to reduce emissions from the majority of the engines in this size range. Reducing DPM emissions to 2.5 g/hr from approximately 9% of engines in this size range that emit more than 20 g/hr of DPM (e.g., Cummins ISB325, General Motors L6T) might be technologically or economically challenging [Bugarksi and Barone 2016]. High DPM emissions translate to short life expectancy of the filters. The DFEs are often changed in intervals not longer than 8 hours which is relatively costly. Replacement of existing engines with same-size engines that meet EPA Tier 4 final standards (PM < 0.015 g/bhp-hr) [EPA 2016] is one of the alternative solutions. However, some replacement engines with high-power outputs might not meet the 2.5 g/hr standard.

Question A.3: ***What costs would the coal mining industry incur to lower emissions of DPM to 2.5 g/hr or less on non-permissible, light-duty, diesel-powered equipment? What are the advantages and disadvantages of requiring that light-duty, diesel-powered equipment emit no more than 2.5 g/hr of DPM?***

Reply A.3: Introduction of the 2.5 g/hour standard should substantially reduce DPM emissions from at least 77% of light-duty vehicles [MSHA 2016a]. Because light-duty vehicles account for approximately 67% of all diesel-powered vehicles currently in U.S. underground coal mines [MSHA 2016a], when the changes required by the standard are implemented it is expected to result in substantial reductions in exposures of underground miners to DPM.

NIOSH has determined that this change in the standard would require retrofitting a substantial number of existing light-duty vehicles with DPFs and filtration systems with DFEs or repowering those vehicles with similar-size engines that meet EPA Tier 4 final standards.

We cannot comment as to the costs of the retrofits, but manufacturers of the equipment may be able to address this issue.

Question A.4: ***What percentage of non-permissible, light-duty, diesel-powered equipment operating in underground U.S. mines do not meet the current EPA emissions standards?***

Reply A.4: Currently, the EPA requires that non-road diesel engines meet the Tier 4 final emissions standard [40 CFR 1039; EPA 2016]. In order for an engine to meet the requirements of Tier 4, the emissions of carbon monoxide (CO), non-methane hydrocarbons (NMHC), nitrogen oxides (NO_x), and PM need to be at or below the standards listed in Table 1.

Table 1. EPA Tier 4 final standards [g/kWh (g/bhp hr)]

Engine Power	Year	CO	NMHC	NMHC+NO_x	NO_x	PM
kW < 8 (hp < 11)	2008	8.0 (6.0)	-	7.5 (5.6)	-	0.4 (0.3)
8 ≤ kW < 19 (11 ≤ hp < 25)	2008	6.6 (4.9)	-	7.5 (5.6)	-	0.4 (0.3)
19 ≤ kW < 37 (25 ≤ hp < 50)	2013	5.5 (4.1)	-	4.7 (3.5)	-	0.03 (0.022)
37 ≤ kW < 56 (50 ≤ hp < 75)	2013	5.0 (3.7)	-	4.7 (3.5)	-	0.03 (0.022)
56 ≤ kW < 130 (75 ≤ hp < 175)	2012-2014	5.0 (3.7)	0.19 (0.14)	-	0.40 (0.30)	0.02 (0.015)
130 ≤ kW ≤ 560 (175 ≤ hp ≤ 750)	2011-2014	3.5 (2.6)	0.19 (0.14)	-	0.40 (0.30)	0.02 (0.015)

Our analysis of the national coal diesel inventory data [MSHA 2016a] indicates that currently only engines in 6 out of 3,411 non-permissible, light-duty, diesel-powered equipment meet EPA Tier 4 final standards [EPA 2016]. Therefore, based on the data in MSHA [2016], approximately 99.8% of engines in the non-permissible, light-duty, diesel-powered equipment do not meet the current EPA emissions standard.

Question A.5: ***What modifications could be applied to non-permissible, light-duty, diesel-powered equipment to meet current EPA emissions standards? What percentage of this equipment could not be modified to meet current EPA emissions standards? If these are specific types of equipment, please list the manufacturers and model numbers.***

Reply A.5: Theoretically, modifications in order to meet EPA Tier 4 final emissions standards would involve retrofitting existing engines with advanced integrated exhaust aftertreatment systems to control PM, NMHC, CO, and NO_x emissions. Certain types of DPF systems (or filtration systems with disposable filter elements), diesel oxidation catalytic converters (DOCs), and selective catalyst reduction (SCR) systems are currently used successfully to control diesel emissions [Bugarski et al. 2012a]. In practice, the design and extent of modifications needed for existing equipment and the success of intervention is dependent on the specifics of individual applications.

Due to the technological challenges of integrating advanced exhaust aftertreatment systems with existing engine systems and their long-term operation over a wide variety of duty cycles in the challenging environment of underground mines, the success of some retrofit programs is uncertain. In particular, reducing DPM emissions from engines that emit more than 20 g/hr of DPM to Tier 4 final levels presents major technologic and economic challenges [Bugarski and Barone 2016]. Repowering existing vehicles with the power packages offered by original equipment manufacturers which meet EPA Tier 4 final standards [EPA 2016] is likely a more plausible solution than retrofitting existing engines with advanced exhaust aftertreatment systems. In the U.S., most engine manufacturers currently offer diesel-power packages with advanced emissions control systems integrated into the engine systems.

Question A.6: ***What are the advantages, disadvantages, and costs associated with requiring all non-permissible, light-duty, diesel-powered equipment operating in underground coal mines to meet current EPA emissions standards? Please be specific and include the rationale for your response.***

Reply A.6: The primary intent of EPA Tier 4 technology-forcing regulations [40 CFR 1039] was to reduce both DPM and NO_x emissions for currently used engines (predominantly EPA Tier 2 and 3 engines) by approximately 90%. The advantage of replacing currently used engines in the majority of currently used light-duty vehicles [MSHA 2016a] with those that meet EPA Tier 4 final emissions standards is that this change should result in substantially lower contributions of PM mass and NO_x concentrations in underground coal mines. Because light-duty vehicles make up approximately 67% of all vehicles currently in U.S. underground coal mines [MSHA 2016a], the change in the standard is expected to result in lower exposures of underground miners to DPM and improve miners' protection from lung cancer as summarized in the MSHA RFI Background section. However, the disadvantage is that such a requirement would potentially result in the need to repower the majority of existing 25+ hp engines with power packages offered by original equipment manufacturers which meet the EPA Tier 4 final standards.

Question B.8: ***What would be the advantages, disadvantages, safety and health benefits, and costs of testing non-permissible, light-duty, underground diesel-powered equipment on a weekly basis for carbon monoxide as required for permissible diesel-powered equipment and non-permissible, heavy-duty, diesel-powered equipment?***

Reply B.8: Testing of non-permissible, light-duty, underground diesel-powered equipment periodically, such as on a weekly basis, for carbon monoxide (and potentially additional pollutants) would be critical to keeping emissions at certification levels. Current regulations [30 CFR 72.500; 30 CFR 72.501; 30 CFR 72.502] indirectly limit personal exposures of underground miners to diesel aerosols by limiting tailpipe PM emissions. In light of these regulations, maintaining in-use engine emissions at certification levels during the entire engine life and using effective aftertreatment technologies are critical to providing adequate protection to miners. Emissions-based engine and exhaust aftertreatment maintenance [McGinn et al. 2010] are very important tools in reducing the exposure of underground miners to diesel aerosols and gases.

Question B.9: ***Reducing the emissions of nitric oxide (NO) and nitrogen dioxide (NO_2) is one way that engine manufacturers can indirectly control particulate production. What are the advantages, disadvantages, and costs of expanding exhaust emissions tests to include NO and NO_2 to determine the effectiveness of emissions controls in underground coal mines? Please provide data and comments that support your response.***

Reply B.9: The formation of PM and NO_x inside the combustion chamber is greatly affected by a number of engine parameters, including air-to-fuel ratio and temperature [Heywood 1988]. In general, the relationship between PM and NO_x emissions is inverse, and controlling NO_x and PM emissions from traditional diesel engines involves a trade-off [Johnson 2009]. For example, in the case of traditional diesel engines, high-temperature combustion results in lower PM emissions but higher NO_x emissions and vice versa. Therefore, reducing the emissions of nitric oxide (NO) and nitrogen dioxide (NO_2) is not an effective method of indirectly controlling particulate production. However, the results of such measurements could be used to periodically assess the performance of an engine and the effectiveness of exhaust aftertreatment systems [McGinn et al. 2010]. The measurement of NO and NO_2 emissions is particularly critical in monitoring the performance of catalyzed exhaust aftertreatment devices such as DOCs converters, catalyzed DPF systems [MSHA 2011], and SCR systems. The results of continuous measurement of NO_x emissions over the duty cycle are critical for optimizing the performance of SCR systems.

Question B.10: ***Should MSHA require that diagnostics system tests include engine speed (testing the engine at full throttle against the brakes with loaded hydraulics), operating hour meter, total intake restriction, total exhaust back pressure, cooled exhaust gas temperature, coolant temperature, engine oil pressure, and engine oil temperature, as required by some states? Why or why not?***

Reply B.10: Engine speed, operating hour meter, total intake restriction, total exhaust back pressure, cooled exhaust gas temperature, coolant temperature, engine oil pressure, and engine oil temperature are some of the engine parameters that are regularly recorded during laboratory emissions testing [30 CFR Part 7; 40 CFR Part 1065; Directive 97/68/EC]. These parameters are critical to the validity of any emissions testing, should be required for periodic emissions testing, and would be critical to the success of any emissions-assisted maintenance efforts [McGinn et al. 2010].

Question C.15: ***What are the advantages, disadvantages, and relative costs of using DPM filters capable of reducing DPM concentrations by at least 75 percent or by an average of 95 percent or to a level that does not exceed an average concentration of 0.12 milligrams per cubic meter (mg/m3) of air when diluted by 100 percent of the MSHA Part 7 approved ventilation rate for that diesel engine? How often do the filters need to be replaced?***

Reply C.15: Filtration systems with DFEs and DPFs are currently used extensively in underground coal mines in the U.S. According to the data in the national coal diesel inventory [MSHA 2016a], more than 370 heavy-duty permissible packages include filtration systems with DFEs. Over 1,140 non-permissible, heavy-duty engines are retrofitted with DPFs or filtration systems with DFEs to meet MSHA [30 CFR 72.501], Pennsylvania [PADEP 2009], and West Virginia [WVMHST 2016] standards. Over 670 light-duty vehicles are equipped with DPFs or filtration systems with DFEs [MSHA 2016a] to meet these standards [30 CFR 72.502]. Only a few recently certified non-permissible engines with integrated DPM controls [MSHA 2016a] do not require an additional ventilation or filter to comply with the 2.5 g/hr standard or 0.12 mg/m^3 standard.

For the majority of currently used engines that need to meet the 2.5 g/hr standard [MSHA 2016a], reducing the DPM emissions to the level of 120 µg/m^3 would require additional air or a higher-efficiency filter. The success of the current regulations [30 CFR 72.500; 30 CFR 72.501; 30 CFR 72.502] strongly depends on the in-use effectiveness of exhaust aftertreatment, specifically filtration systems with DFEs and DPFs. In support of the intent of the regulations to protect the health of underground miners, we assess that the DFEs used in the underground coal mining industry should meet more stringent standards to secure use of the products that provide adequate protection. One area that requires improvement is the efficiency of DFEs throughout their useful life [Bugarski et al. 2011; Bugarski 2016; Davies 2016].

In general, the current procedures for the certification of diesel engines and verification of exhaust aftertreatment technologies need to be improved to accommodate for differences in the variety of deployed diesel engines and exhaust aftertreatment technologies [Thiruvengadam et al. 2012; Herner et al. 2011; Robinson et al. 2016]. The procedures should detect the potential for the generation of secondary emissions of toxic substances that are not part of the original engine-out emissions [Czerwinski et al. 2007; Heeb et al. 2008]. Therefore, to use adequate technologies that offer both reduction in particulate mass as well as in particle number emissions [Mayer et al. 2009a], the standards should be modified to include reference to exhaust particulate number concentrations [FOEN 2016].

Current regulations [30 CFR 72.500; 30 CFR 72.501; 30 CFR 72.502] indirectly limit personal exposures of underground miners to diesel aerosols and gases by limiting tailpipe emissions. Given these regulations, maintaining in-use engine emissions at the certification level during the entire engine life and using effective aftertreatment technologies are critical to providing adequate protection to miners. Due to sufficient reliability and durability, diesel engines are used in underground mines for many years, and engines are often rebuilt several times during their useful life. More stringent standards, as described above, are needed to ensure that in-use emissions from diesel-powered vehicles operated in underground mines are close to certification level emissions. Similarly, the in-use performance of exhaust aftertreatment technologies should be periodically verified during the device's useful lifetime.

Finally, advancements in portable emissions measurement systems (PEMS) make periodic examination of in-use emissions from operating vehicles feasible [Vlachos et al. 2014]. Typical PEMS integrate gas and particulate analyzers, exhaust mass flow meters, and connection to the engine/vehicle management systems. PEMS allow for real-time monitoring of the currently regulated pollutants emitted by engines (CO, CO_2, NO, NO_2, and PM) and other pertinent engine parameters.

Question C.16: ***What sensors (e.g. ammonia, nitrogen oxide (NO), nitrogen dioxide (NO_2) are built into the aftertreatment devices used on the diesel-powered equipment?***

Reply C.16: A sensor for measurement of NO_x emissions upstream and downstream of a SCR system is available from Continental Automotive (Smart NOx Sensor UniNOx) [Continental 2016]. The sensor measurement results are used to control urea dosing and to diagnose the operation of the SCR system. A sensor for measurement of ammonia levels in the exhaust of diesel vehicles equipped with an SCR aftertreatment system (0 to 100 ppm) is available from Delphi [Delphi 2016]. The sensor output can be used to provide feedback to the SCR system, helping to provide optimal reduction of NO_x emissions [Wang et al. 2007].

Question C.18: ***What are the advantages, disadvantages, and relative costs of requiring that all light-duty diesel-powered equipment be equipped with high-efficiency DPM filters?***

Reply C.18: Light-duty vehicles have been found to be responsible for a major fraction of the DPM burden in underground metal mines [Rubeli et al. 2004]. Currently, over 670 light-duty, non-permissible vehicles are successfully operated in underground coal mines with high-efficiency DPFs or filtration systems with DFEs [MSHA 2016a].

If retrofitted with high-efficiency DPM filters, light-duty diesel-powered equipment would contribute substantially less to the concentration of DPM in the underground environment. However, retrofitting existing light-duty vehicles with high-efficiency DPM filters would involve significant technological challenges including lack of regeneration strategies, physical size of the systems, and higher complexity. For some applications, it could be more feasible to repower vehicles with engines that meet EPA Tier 4 final standards [EPA 2016].

Question D.24: ***MSHA requests information on alternative surrogates, other than TC, to estimate a miner's DPM exposure. What is the surrogate's limit of detection and what are potential interferences in a mine environment?***

Reply D.24: NIOSH does not have sufficient data to recommend an alternative surrogate to the currently used combination of total carbon (TC) and elemental carbon (EC). A number of factors make sampling, analysis, and direct measurement of DPM in the occupational environment or in the tailpipe challenging. These factors include submicron size, relatively low-mass concentrations when compared to total particulates in the air, complex physical and chemical makeup, the dynamic nature of formation and transformation of DPM, interactions within the environment, potential interferences with other sources of aerosols, and a large number of physical and chemical processes that affect the formation and transformation of diesel aerosol particles [Bugarski et al. 2012b]. Thus, a detailed characterization of diesel aerosols often requires multiple measurements using various sampling techniques and instruments, elaborate sampling strategies, and careful interpretation of the results.

Currently, TC and EC are both used as surrogates to monitor exposure of underground metal and nonmetal miners to DPM [71 Fed. Reg. 28924]. This approach has a number of deficiencies, but also some major advantages. The results of the TC concentration monitoring are prone to the generation of artifacts due to issues related to monitoring the organic fraction of TC. The positive and negative artifacts are related to potential sampling interference, adsorption of the gas-phase volatile and semi-volatile species on the quartz filter media, desorption of volatile droplets or particle-bound volatile material from the filter media, and filter media handling [Bugarski et al. 2012b]. Mechanically generated dust, cigarette smoke, welding fumes, oil mist, and gas phase organics emitted by diesel engines can interfere with the TC measurements. The current practices to minimize the effects of some of these interferences are: (1) sampling with a 0.8-μm impactor (DPM cassette, SKC 225-317) to minimize the contribution of mechanically generated dust to DPM samples; (2) preventing sampling in the presence of cigarette smoking, welding, and drilling; and (3) applying dynamic blank correction to correct for adsorption of gas-phase volatile and semi-volatile species on the quartz filter media [Noll et al. 2005; Noll et al. 2006; Noll and Birch 2008]. Using EC as a supplemental surrogate could potentially ensure compliance with a permissible exposure limit (PEL) when direct measurements of TC are not producing accurate results due to organic carbon (OC) related errors. However, the uncertainties associated with establishing a mine-specific TC/EC ratio [71 Fed. Reg. 28924] might contribute to the overall uncertainty of the results.

An approach that involves using EC as a stand-alone surrogate to DPM would potentially eliminate some of the sampling and analytical uncertainties, but might not be equally protective to miner's health as the TC/EC approach. In most U.S. underground mines, EC is selective and unique to DPM and makes up a significant portion of the DPM mass [Birch and Cary 1996a; Birch and Cary 1996b; Birch et al. 1999; Birch 2002; NIOSH 2016; Noll et al. 2006]. For the few mines that have small quantities of EC in the dust, the submicron particle-size classifier in the SKC DPM cassette would minimize this interference because dust size is typically greater than 1 micron [Noll et al. 2006; Noll et al. 2005]. Cigarette smoke and oil mist should not significantly interfere with the EC analysis [Noll et al. 2006]. Thus, the uncertainty in EC measurement, based on thermo-optical carbon analysis [NIOSH 2016], should be reduced relative to TC because potential OC interferences are minimized. And, with an EC surrogate, the uncertainty associated with establishing a mine-specific TC/EC ratio would be eliminated. However, the relationship between the EC and OC or TC depends on engine type, engine operating conditions, fuel type, and exhaust aftertreatment type, and has been recognized as a possible drawback to use of an EC surrogate [66 Fed. Reg. 27864 ; Bugarski et al. 2012b; Khalek et al. 2011]. The correlation between EC and TC in underground mining samples, where predominantly traditional diesel technology is used, has been found to be fairly predictable; however, establishing a single TC/EC ratio at the final exposure limit of 160 $\mu g/m^3$ TC was not possible [Noll et al. 2007]. A strong relationship between TC and EC at the 160 $\mu g/m^3$ TC limit was established for fourteen underground mines that were using several different types of control technologies and strategies [Noll et al. 2015]. However, there is a concern that control mitigation strategies will be developed where EC is no longer a good representative of DPM. More prevalent use of exhaust aftertreatment technologies in the future might significantly alter the composition of DPM, notably the EC and OC content [Bugarski et al. 2010].

The additional protection of underground miners' health with respect to exposure to DPM may be achieved by improving the process of monitoring personal exposure of miners working in underground metal and nonmetal mines, by introducing the monitoring of personal exposure of miners working in coal mines, and by improving procedures for the certification of diesel engines and verification of exhaust aftertreatment technologies, as described below.

- **Introduction of an additional metric or metrics for monitoring exposure of underground miners to DPM:** An additional metric for total DPM, TC, and/or EC mass should be considered in order to protect workers from DPM aerosols. The current practice is to monitor exposure of miners in U.S. underground metal/nonmetal mines [71 Fed. Reg. 28924] and characterize emissions [61 Fed. Reg. 55411] of nano and ultrafine DPM aerosols in terms of TC and EC mass concentrations and total particulate mass. This approach has been adequate to predict exposures and emissions when traditional engines equipped with mufflers and DOCs are considered. However, this approach is relatively insensitive to reductions in the size of diesel aerosols, increases in the concentrations of nucleation mode aerosols, and changes in chemical composition observed after the introduction of contemporary control technologies and strategies [Bugarski et al. 2009; Herner et al. 2011; Khalek et al. 2011]. A new monitoring approach that combines the total carbon (TC) analysis with an additional analytical technique, such as the measurement of the total particle number concentration or surface area concentration, has been proposed [Cauda et al. 2012]. The additional area measurements could be carried out with some of the commercially available portable and hand-held real-time monitors [TSI 2016; NANEOS 2016]. Size-selective samplers should be used to minimize interferences with mechanically generated aerosols and sampling in the presence of cigarette smokers, and welding and/or drilling should be avoided. The instrumentation used to perform these measurements would need to be validated for compliance measurements.

- **Using elemental carbon (EC) as a surrogate to monitor personal exposure of coal miners to DPM:** Current regulations [30 CFR 72.500; 30 CFR 72.501; 30 CFR 72.502] indirectly limit personal exposures of underground coal miners in the U.S. to diesel aerosols and gases by limiting tailpipe emissions. Nonetheless, due to the absence of direct measurements of personal exposure to DPM, verification of the hypothesis that reductions in emissions would provide adequate protection to miners is not possible. In the majority of coal types, only a relatively small portion of submicron coal dust is EC [Birch and Noll 2004; Noll and Birch 2004]. Due to high concentrations of organic compounds in the coal, TC cannot be used as a surrogate for monitoring exposure of underground coal miners to DPM. EC has been successfully used as a surrogate for monitoring exposure in underground coal mines [Birch and Noll 2004; Noll and Birch 2004; Noll et al. 2015]; however, a size-selective sampler has to be used to exclude most of the coal dust in order to minimize the effects of coal dust on EC mass.

- **Improving procedures for certification of diesel engines and verification of exhaust aftertreatment technologies:** The current procedures for the certification of diesel engines and verification of exhaust aftertreatment technologies need to be improved to accommodate for advancements in diesel engines and exhaust aftertreatment technologies [Thiruvengadam et al. 2012; Herner et al. 2011; Robinson et al. 2016] and for tackling the inherent challenges in the quantification of DPM emissions [Swanson et al. 2010]. Improved procedures should detect the potential for the generation of secondary emissions of toxic substances that are not part of the original engine-out emissions [Czerwinski et al 2007; Heeb et al. 2008]. For example, in order to ensure use of adequate technologies that offer both reduction in particulate mass as well as in particle number and surface area emissions, the standards should be modified to include reference to exhaust particulate number and surface area concentrations. As one recent example, particulate-number-based regulations have been adapted by the Swiss government [FOEN 2016].

Question D.25: ***What are the advantages, disadvantages, and relative costs for using the alternative surrogate to determine a MNM miner's exposure to DPM? Please be specific and include the rationale for your response.***

Reply D.25: If EC were used in place of TC and EC as a DPM surrogate, the number of samples and analyses needed to determine exposure would be reduced. Further, the analysis of area samples to derive a conversion factor for converting the EC results for personal samples to TC equivalents would not be necessary. Additionally, when using EC, there would be no need to analyze a dynamic blank (i.e., a bottom filter in cassette with tandem filters) to correct for adsorbed OC—an approach which MSHA employs for at least the area samples. However, using EC as a surrogate for DPM has several potential limitations, including the dependence of the relationship between the EC and TC/DPM on engine type, engine operating conditions, fuel type, and exhaust aftertreatment [66 Fed. Reg. 27864; Bugarski et al. 2012b; Khalek et al. 2011], and the absence of any information on the toxicologically and health-pertinent organic fractions of DPM [Totlandsdal et al. 2012; Turner et al. 2015].

As knowledge of the health effects of exposure to diesel emissions becomes refined, it may be important to introduce other metrics to monitor exposure. Particle number, surface area, or size distribution may provide better monitoring, hazard assessment, and risk management related to the exposure to diesel aerosols emitted from contemporary engines and control technologies, particularly those with high mass-specific surface areas. When these technologies are implemented, the assessment of the DPM exposure of underground miners may not be comprehensive if the monitoring is limited to TC and EC [Cauda et al. 2012]. In particular, the current practice of monitoring exposure of miners in U.S. underground metal/nonmetal mines [71 Fed. Reg. 28924] to nano and ultrafine DPM aerosols in terms of TC and EC mass concentrations might not be sufficient to adequately assess exposures to DPM when changes occur in the size of diesel aerosols [Bugarski et al. 2009; Bugarski et al. 2010], concentrations of nucleation mode aerosols [Bugarski et al. 2009; Herner et al. 2011], and in chemical composition [Bugarski et al. 2010; Khalek et al. 2011; Herner et al. 2011] after the introduction of contemporary control technologies and strategies. These types of monitoring strategies still need further development and validation.

Question D.26: ***MSHA requests information on advances in sampling and analytical technology and other methods for measuring a MNM miner's DPM exposure that may allow for a reduced exposure limit.***

Reply D.26: If EC is used in place of currently used TC and EC as a DPM surrogate, the NIOSH Analytical Method 5040 would be adequate to assess DPM concentrations at compliance levels (and much lower) in metal/nonmetal (MNM) and coal underground mines. NIOSH 5040 limit of detection (LOD) for EC is about 2.0 μg/m^3 for a 960-L air sample collected on a 37-mm filter, with a 1.5-cm^2 punch from the filter analyzed. If a lower LOD is desired, a larger sample volume and/or a 25-mm filter may be used. If a 1920-L sample is collected on a 25-mm filter, an LOD of about 1.0 μg/m^3 can be achieved [NIOSH 2016]. Increasing the flow rate would require development of a new size selector that offers a similar cut point to the SKC impactor at this increased flow. To permit the use of the SKC DPM cassette, operated at 1.7 liter per minute (lpm) sampling flow rate, the LOD could be reduced by adapting the cassette to accommodate a 25-mm filter instead of the currently used 37-mm filter. The disadvantage of lowering the LOD by using a smaller collection area is that it also reduces the dynamic range (i.e., lowers the upper concentration limit) because the filter will be overloaded at high DPM concentrations, causing variable flow or leakage.

A recent NIOSH study (Cauda et al. [2014]) shows that the performance of the DPM cassette (SKC 225-317) is altered during prolonged sampling in dusty environments. The penetration efficiency of the DPM cassette was found to change with exposure of the sampler to respirable dust particles. Particle penetration efficiency shifts towards smaller sizes with the accumulation of dust particles inside the size separator. This shift can potentially generate negative bias in sampling DPM in the mining environment. A sharp cut cyclone whose penetration efficiency is not affected by respirable dust particles may provide a solution to this problem [Cauda et al. 2014].

NIOSH has developed a near real-time EC monitor [Noll et al. 2013; Noll and Janisko 2013; Noll et al. 2014]. Real-time, on-site measurements with this monitor provide timely information that can be used as an engineering tool to identify factors contributing to overexposures, characterize exposure patterns (e.g., high transient exposures), and allow for quick deployment of engineering controls. The monitor measures the EC concentration via laser extinction.

Question E.27: ***What existing controls were most effective in reducing exposures since 2006? Are these controls available and applicable to all MNM mines?***

Reply E.27: Numerous controls have been implemented effectively to reduce exposures since 2006 and have been thoroughly studied by NIOSH and other organizations, as detailed below.

- **Deploying DOCs:** DOCs have been widely deployed on underground mining vehicles to control CO and hydrocarbon (HC) emissions [Bugarski et al. 2015]. DOCs typically do not affect NO_x emissions, but might adversely affect NO_2 emissions [Stachulak and Gangal 2013; Bugarski et al. 2015]. However, the effects of a DOC on DPM concentrations have been found to be relatively minor and are a function of engine operating conditions and fuel type [Bugarski et al. 2010]. In general, the effectiveness of a DOC as a DPM control is primarily dependent on the fraction of OC present in the engine exhaust, because the total PM reduction efficiency increases with an increase in OC content of the exhaust [Shah et al. 2007].

- **Using DPF and DFE systems:** DPF systems, certified and/or verified by a number of organizations [MSHA 2015; FOEN 2016], are extensively used in underground mining and other industries to curtail DPM emissions. DPF systems for underground mining applications have been extensively evaluated in long-term studies [Stachulak et al. 2005; McGinn et al. 2004], short-term studies [NIOSH 2006a,b; Bugarski et al. 2009; Bugarski et al. 2012a], and laboratory studies [Bugarski et al. 2013; Bugarski et al. 2016a]. The evaluated DPFs removed, in the majority of test cases, at least 90 percent of the particles by mass and number. Over 670 light-duty vehicles, equipped with DPFs or a filtration system with disposable filter elements (DFEs) [MSHA 2016a] to meet 30 CFR 72.502, are effectively being used in underground coal mines in the U.S.

- **Implementing pDPFs or FTFs:** Partial-flow DPFs (pDPFs) or flow-through filters (FTFs) are currently used in a few applications in U.S. underground mines. These are simpler, less costly, and less effective solutions for applications where DPF systems might be difficult to implement. Under steady state conditions, pDPF/FTF of various designs were found to be between 6% and 70% efficient in reducing the number of diesel aerosols [Mayer et al. 2009b; Heikkilä et al. 2009]. An on-road test showed substantial fluctuations in performance of pDPFs/FTFs [Mayer et al. 2009b]. In practice, due to the dynamics of the filtration, regeneration, and potential for sudden release of trapped DPM, it is very difficult to reproduce data and produce reliable estimates of filter efficiency.

- **Changing Fuel Supply from USLD to FAME and/or HVORD:** Changing the fuel supply from petroleum diesel to fatty acid methyl ester (FAME) biodiesel and/or hydrotreated vegetable oil renewable diesel (HVORD) is considered by a number of underground metal and nonmetal mine operators in the U.S. to be a viable method for controlling DPM emissions and complying with current MSHA regulations [30 CFR 57.5060]. Currently, U.S. underground mines using biodiesel fuels are almost exclusively using FAME biodiesels, which are made from various vegetable oils and animal fats through the process of transesterification [Graboski and McCormick 1998]. When compared to low sulfur and ultralow sulfur petroleum diesels (LSD and ULSD), FAME biodiesels reduce emissions of total DPM and nonvolatile fractions of DPM [Bugarski et al. 2010] and, under certain engine operating conditions, can increase the particle-bound volatile organic fraction of DPM [Stackpole 2009; Bugarski et al. 2010]. In-use studies have shown the potential of neat soy methyl ester (SME) FAME [Bugarski et al. 2010] and SME biodiesel blends [NIOSH 2006a,b; Bugarski et al. 2010; Bugarski et al. 2014] to reduce the exposures of underground miners to EC, TC, and total DPM mass. Substantial increases in emissions of the organic carbon (OC) fractions of TC and DPM have been observed when the engine was fueled with SME FAME fuels and operated at light-load conditions [Schönborn et al. 2009; Bugarski et al. 2010]. Further, when compared to those emissions generated by combustion of ULSD, FAME biodiesel aerosols were found to have higher toxicity [Yanamala et al. 2013] and to cause more abnormalities in male mice reproductive systems [Kisin et al. 2014].

  Recently, some underground operations in the U.S. started fueling their diesel-powered equipment with blends of hydrotreated vegetable oil renewable diesel (HVORD). These fuels are derived from vegetable and algae oils and animal fats via the hydrogenation and isomerization process. HVORD is almost exclusively made of paraffinic and iso-paraffinic hydrocarbons and is virtually free of aromatic hydrocarbons, metals, sulfur, nitrogen, and oxygen-containing compounds. HVORD, in general, has favorable effects on PM mass and NO_x

emissions, and minor effects on CO and total hydrocarbon emissions [Stevanovic et al. 2013; Westphal et al. 2013; Kim et al. 2014; Bugarski et al. 2016b]. When compared with FAME biodiesel fuels, HVORD produces lower NO_x and higher CO, total hydrocarbons, and PM mass and number emissions [Westphal et al. 2013; Kim et al. 2014; Bugarski et al. 2016b]. Finally, HVORD has the potential to adversely affect NO_2 emissions from naturally aspirated engines equipped with certain types of DOCs [Bugarski et al. 2016b].

- **Using Environmental Cabins with Pressurization and Filtration Systems:** Enclosing operators in environmental cabs with pressurization and filtration systems was found to help some parts of the underground mining industry in efforts to reduce the exposure of workers to DPM [Noll et al. 2014]. Environmental cabs have been a viable DPM control strategy in cases where the majority of the duties can be executed by workers that do not have to leave their environmental cabs on a frequent basis. Further, the effectiveness of several types of filtration elements used in the filtration systems of underground mining environmental cabins in the removal of diesel aerosols (EC and TC mass) has been assessed in both the NIOSH laboratory and the field [Noll et al. 2014]. Finally, two types of minimum efficiency reporting value (MERV) 16 filters were found to be 94% and 98% effective in removing diesel aerosols. Two types of high efficiency particulate air (HEPA) filters removed over 99% of diesel aerosols. With a relatively low cost and good efficiency, MERV 16 filters were found to be a viable alternative to substantially more expensive and flow-restrictive HEPA filters [Noll et al. 2014].

- **Treating Crankcase Emissions:** Crankcase emissions have proven to be a large contributor to overall particulate emissions from older diesel engines [Hill et al. 2005]. As a result of successful efforts in reducing tailpipe emissions, the relative contribution of crankcase emissions to overall emissions is becoming more and more significant. If crankcase emissions are not treated, blowby can contribute as much as 20% of the mass total PM emissions from EPA Tier 2 and Tier 3 engines and exceed the tailpipe emissions of EPA Tier 4 engines [Jääskeläinen 2009]. This issue is addressed by selected regulations promulgated by the U.S. EPA [40 CFR 1039.115] and the EU Commission [EUCD 2012]. As the regulations note, crankcase emissions from HD and LD underground mining vehicles should not be discharged directly into the underground mine atmosphere. If such discharges cannot be technically prevented, at least during engine certification, those emissions should be included in the total engine emissions.

DISCLAIMER

Mention of company names or products does not constitute endorsement by the Centers for Disease Control and Prevention.

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